Piezoelectric Microresonators Based on Aluminim Nitride for Mass Sensing Applications

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***Abstract*—In this work we analyze the vibrational behavior of microresonators (cantilevers and bridges) actuated with piezoelectric aluminum nitride (AlN) films, to investigate the suitability of these devices as mass sensors. The resonators of different geometries consisted of a freestanding unimorph structure made up of a metal/AlN/metal piezoelectric stack supported by a Si_3N_4 structural layer. The out-of-plane motion of the resonators was assessed by laser interferometry. The electrical impedance of the devices exhibited significant variations at some resonant frequencies ranging from 0.5 MHz to 13 MHz. The mass sensitivity of the microresonators was evaluated through the frequency shift of the resonant modes when loading the resonators with SiO_2 films. High order resonant modes provided higher mass sensitivities, with values as low as 6 ag/Hz, which improved significantly our previous results.**

I. INTRODUCTION

Micromechanical resonators based on freestanding unimorph structures (microcantilevers and microbridges) can be used as gravimetric transducers as they undergo changes in their resonant frequency when loaded with an additional mass [1]. To be used as high-resolution gravimetric transducers, high resonant frequencies are desirable, as the relative variations of the resonant frequency are proportional to the relative variations of mass [2]. High resonance frequencies are obtained in stiffer structures, which can be achieved by decreasing the dimensions of the devices [3], or by increasing either the elastic constants of the materials involved [4] or the stress of the layers [5].

Among the different ways used to produce the movement of the freestanding microstructures, piezoelectric actuation offers the advantage of low actuation voltages and moderate power consumptions [6]. Piezoelectric flexural resonators are based on the mechanical bending experienced by unimorph structures (piezoelectric/structural layer) when an external field perpendicular to the surface is applied. The electric field induces a longitudinal extension (or contraction) of the piezoelectric layer, proportional to the piezoelectric coefficient d_{31}. The internal in-plane stress built in this piezoelectric layer produces the bending of the freestanding structure in the vertical direction [2]. PZT and ZnO have been the piezoelectric layers of choice in the last years for piezoelectrically actuated devices [7-9]. The recent advances in AlN films for acoustic wave devices, such as bulk acoustic wave (BAW) [10], surface acoustic wave (SAW) [11] or contour mode [12] resonators, suggest their use in piezoelectric mechanical resonators [4]; AlN films are fully compatible with conventional silicon micromachining technologies and offer interesting properties for mass sensor applications, such as high chemical and thermal stabilities and good piezoelectric properties.

An interesting characteristic of piezoelectrically driven resonators is the possibility of detecting the mechanical resonances through the changes of the electric admittance of the piezoelectric layer [13]; this provides an all-electric method for actuation and sensing, thus avoiding the complex optical procedures for the detection of motion. By using simultaneously the inverse and direct piezoelectric effects, a single pair of electrodes is required for both actuation and sensing, providing a one-port device: the electrical signal is used simultaneously for excitation and detection, which simplifies significantly the electronics.

In this communication we report the fabrication and characterization of freestanding microcantilevers and microbridges actuated piezoelectrically with AlN films, which act simultaneously as actuators and detectors of the motion. We show that some of the vibrational modes detected by conventional optical interferometry are easily assessed through the measurement of the electrical admittance of the one-port device. We investigate the influence of the structure (microcantilever or microbridge) on the vibrational behavior of the devices in order to identify which one provides the higher sensitivity for mass detection.

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II. EXPERIMENTAL DETAILS

Freestanding microstructures (cantilevers and bridges) of different geometries were fabricated on silicon substrates using conventional surface micromachining techniques.

Figure 1 shows scanning electron microscope images of two typical devices.

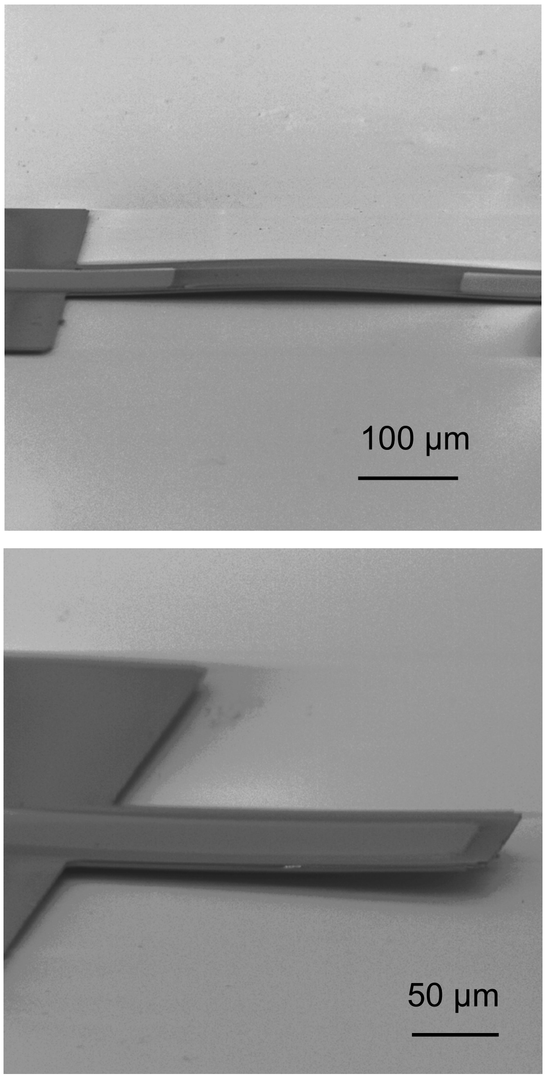

Fig. 1. Image of (a) a microbridge of 500 µm x 100 µm and (b) a microcantilever of 175 µm x 60 µm obtained by scanning electron microscope.

All the films were deposited by pulsed-DC sputtering under controlled deposition conditions to minimize their in-plane residual stress. The resonators consisted on Mo/AlN/Mo capacitors supported by Si_3N_4 structural layers. The whole structures were grown on top of a 3.3 µm-thick silicon oxide sacrificial layer of low density, sputtered in a mixture of argon and oxygen. This layer exhibited a residual stress lower than 200 MPa and a surface roughness lower than 5 nm rms, as measured by AFM; it was easily etched in BFH solutions. The thickness of the Si_3N_4 structural layer was adjusted to 1 µm; its compressive residual stress of around 600 MPa was partially removed after releasing the whole structure. The piezoelectric stack was formed by an AlN film sandwiched between two 100 nm-thick Mo electrodes. A 30 nm-thick Ti layer under the Mo bottom electrode acted both as adherent and seed layer. The AlN films were sputtered to a thickness of 1 µm; the residual stress was minimized by adjusting carefully the bias voltage applied to the substrate. Their longitudinal piezoelectric coefficient, d_{31}, was assessed through the electrical measurements of SAW delay lines built on top of AlN films of identical characteristics than those used for devices fabrication, following the procedure described previously [14]. A d_{31} mean value of 1.6 pm/V was derived from the longitudinal electromechanical coupling factor (k_{l2}) obtained from the SAW devices [15].

The mechanical motion of the microresonators was first assessed by laser interferometry measurements. The interferences of a laser beam reflected on both the mobile and the fixed parts of the device were detected with a fast Avalanche Photodiode (APD) model TIED87 whose output was amplified and fed to an Agilent ESA4402 spectrum analyzer. The microresonators were excited through the tracking generator of the spectrum analyzer with a signal of around 1 V of amplitude at frequencies varying between 10 kHz and 13 MHz. The vibrational resonances were also assessed through electrical measurements in the same frequency range. The electrical impedance of the devices was measured as a function of the frequency with an Agilent HP-4192A impedance analyzer. A peak voltage of 1.1 V was used for the measurement to have a similar driving than in the previous technique. The impedance of the microcantilevers was represented by a simple parallel circuit consisting in a capacitor (imaginary part of the admittance divided by the angular frequency) in parallel with a resistor (the real part of the admittance). This circuit is actually not a model but only a representation of the admittance of the device at a given frequency.

To investigate the suitability of these devices as mass sensors, the sensitivity of the resonant frequencies of the different vibrational modes to mass loading was estimated for both types of devices, microcantilevers and microbridges using the following procedure. First the frequency response of the devices was assessed by measuring the electrical admittance spectrum. Then a known amount of mass was added on top of the device and the admittance spectrum was recorded again. This sequence loading/measuring was repeated at least three times per sample. As loading we used SiO_2 sputtered thin films whose mass was estimated by measuring with a profilometer the thickness of the film on a test sample, and by multiplying it by the mass density of the SiO_2 and by the freestanding area of each device. The mass density of the sputtered SiO_2 thin film was estimated using a thicker layer deposited on a 100 mm in diameter silicon wafer, which was weighted before and after the deposition. The amount of mass added in each loading step was in the picogram range.

III. RESULTS AND DISCUSSION

Figure 2 shows the frequency response of a typical device measured by laser interferometry and electrical admittance (parallel capacitance and conductance).

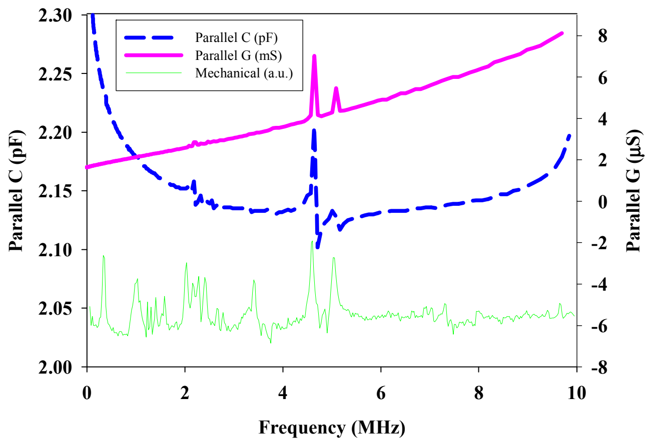

Fig. 2. Mechanical response determined by laser interferometry and parallel capacitance and parallel conductance as a function of frequency for a typical microcantilever.

The interferometric spectrum of figure 2, that shows the out-of-plane movement of the device, reveals the presence of vibrational modes in the whole frequency range. Each peak corresponds to the resonance of a certain vibrational mode induced by the applied field in the piezoelectric capacitor of AlN that forms a unimorph structure with the silicon nitride structural layer. The amplitude of the different vibrational modes is not a measure of the absolute displacement of the structure because, in our experimental setup, the laser beam is not focused in a small part of the microcantilever but rather in a larger area of the mobile structure. Actually, very small displacements of the laser beam over the freestanding structure can produce significant variations of the relative amplitudes of the peaks, while the frequency remains always the same. Therefore, the measured spectrum provides the frequencies of the resonant modes, but do not supply information of their relative intensities. It is important to note that in this work, laser interferometry is only used to confirm that electrical resonances correspond indeed to out-of-plane movements.

The frequency spectra of the parallel capacitance and parallel conductance shown in figure 2 exhibit strong peaks corresponding to some of the motional resonances detected by the interferometric technique. It is worth noting that the interferometric technique detects modes that do not appear in the electrical spectra. In a previous work [16], we have reported that the variations observed in the electrical spectra are related with variations in the detected current due to the effect of the piezoelectric field superimposed to the applied electric field. These "electrically active" modes have been associated with non-symmetric vibrational modes that do produce net variations of the total current. The variations of the electrical impedance allow to assess the motion of the freestanding structures by electrical means, avoiding the complex experimental setup of the interferometric optical measurements. Besides, the use of the same port for both excitation and sensing of the motion convert the sensor in a one-port-device, which is especially convenient for the design of the associated electronics.

To characterize the performance of our devices as mass sensors, we have measured their frequency response after loading with different masses, as described in the experimental section. We used the resonant frequency shift of the devices as the sensing signal. All the resonant modes exhibit significant frequency shifts towards lower frequencies as the mass loading increases; the relative frequency shift is higher for high resonant modes. We have observed a linear variation of the resonant frequency with the added mass within the mass range considered.

Figure 3 shows the parallel conductance, as a function of frequency, for the 2.44 MHz resonant mode of a typical microbridge, after several sequential mass loadings. The inset shows the frequency shift as a function of the added mass. The inverse of the slope of this variation is the mass sensitivity (in g/Hz) [17] used to characterize our devices as mass sensors; the lower the mass sensitivity the better the mass sensor. All the devices (microbridges and microcantilevers of different geometries) show a similar behavior. We have observed that the mass sensitivity of the resonators improves significantly at high frequencies for all the structures, as predicted by theory [11].

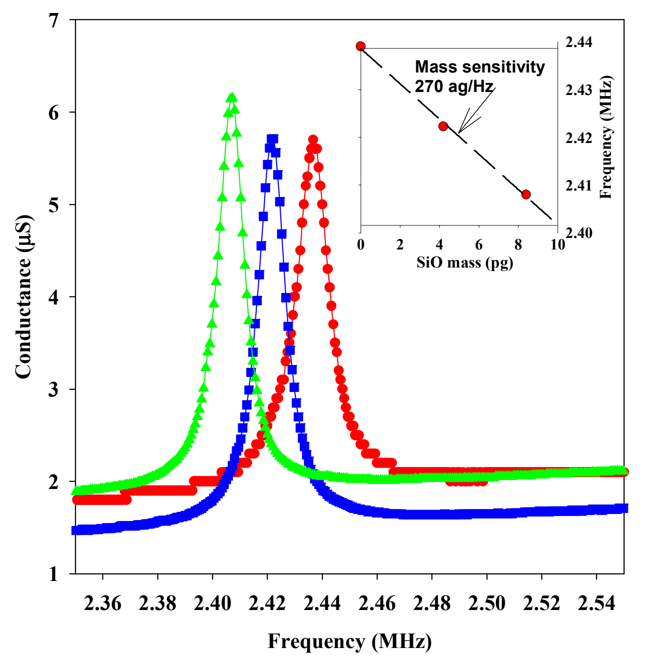

Fig. 3. Parallel conductance resonant mode of a typical microbridge loaded with three different mass loads ((●) 0 pg, (■) 4.2 pg and (▲) 8.4 pg). The inset shows the resonant frequency as a function of the load.

Figure 4 shows the mass sensitivity of microcantilevers and microbridges with different geometries as a function of the resonant frequency. Several resonant modes for each device are shown. As a general rule, the higher frequency modes are more sensitive than those at lower frequency. Besides, the microcantilevers present best values of mass sensitivity than the microbridges for similar frequencies. The best values observed are 5.7 ag/Hz (at 12.39 MHz of frequency) for a microcantilever and 55 ag/Hz (at 10.59 MHz of frequency) for a microbridge.

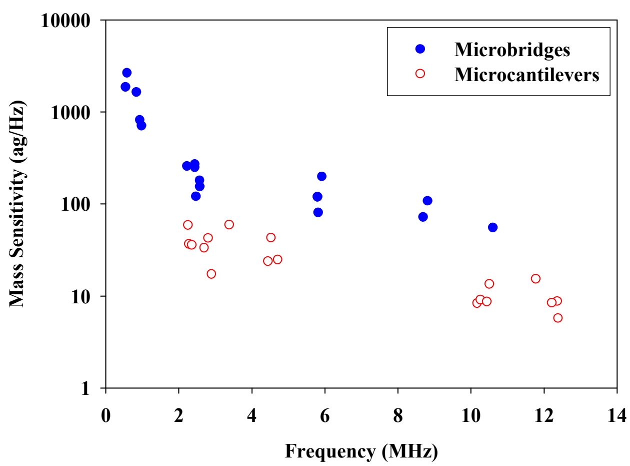

Fig. 4. Mass sensitivity as a function of frequency for microcantilevers and microbridges.

IV. CONCLUSIONS

The frequency response of piezoelectric microresonators (microcantilevers and microbridges) actuated with AlN have been evaluated. The vibrational behavior of the resonators can be assessed in a very convenient way through the variations with frequency of the electrical impedance of the AlN capacitor. Used as mass sensors, the sensibility of the microcantilevers and the microbridges is better for high frequency modes. The microcantilevers show a better response in all the frequency range. Our devices exhibit values for the sensibility as low as 5.7 ag/Hz, for the microcantilevers, and 55 ag/Hz, for the microbridges, at a frequency of around 10 MHz.

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